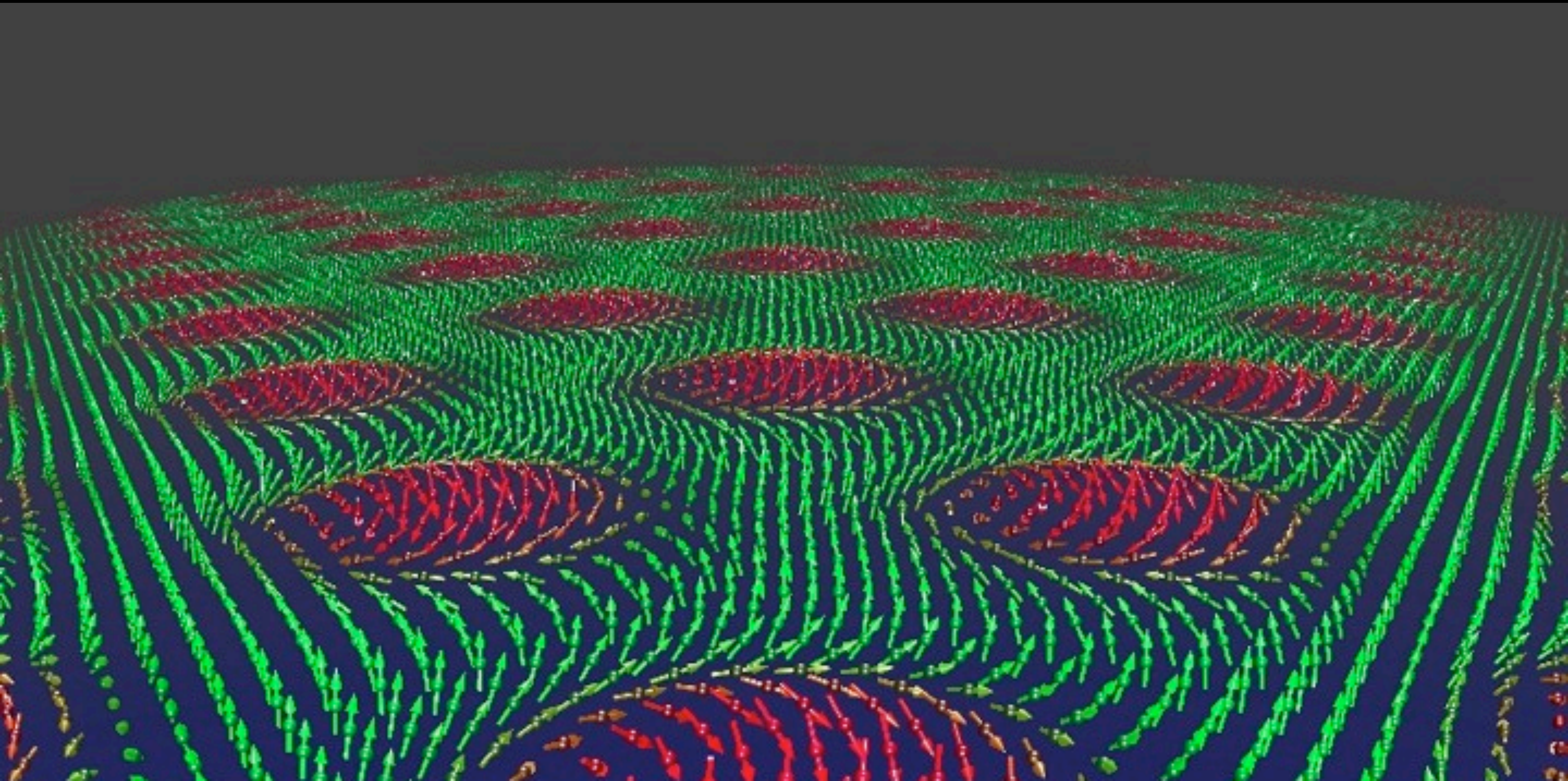
Spin-transfer torques and emergent electrodynamics in magnetic Skyrmion crystals

Markus Garst Universität zu Köln



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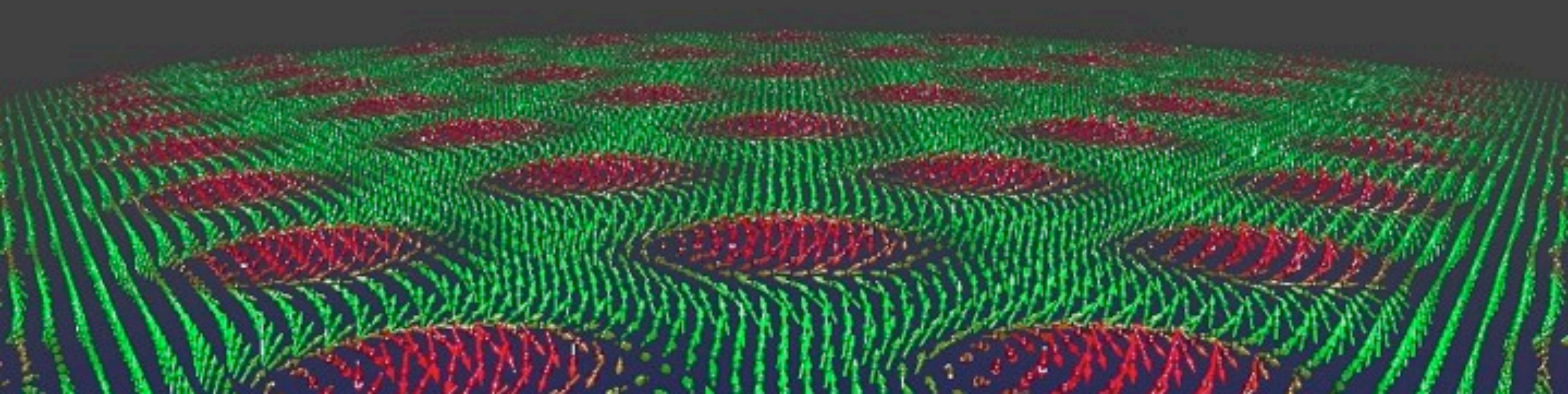
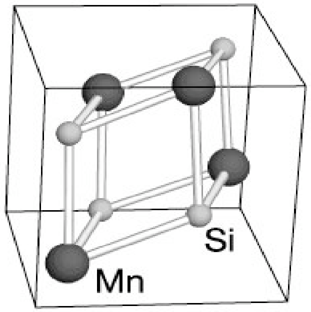


Itinerant chiral magnets

MnSi, $Fe_{1-x}Co_xSi$, MnGe, FeGe,...

Bravais lattice: simple cubic

point group: $P2_13$ (B20)

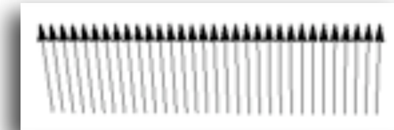


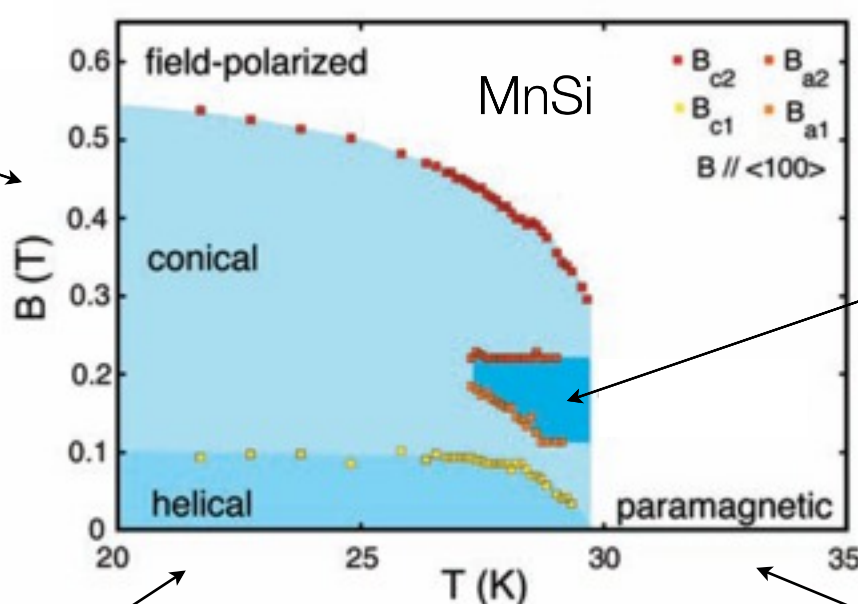
no inversion symmetry

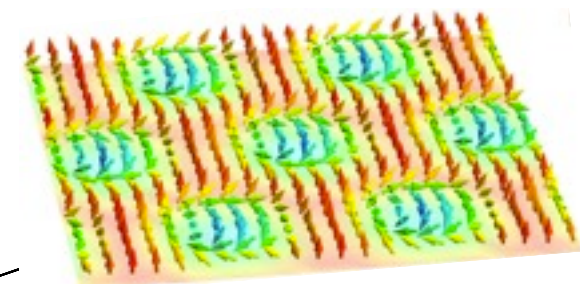
⇨ **chiral** magnetism

magnetisation: helical ground state

Chiral magnets in a magnetic field

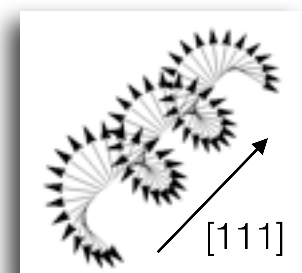


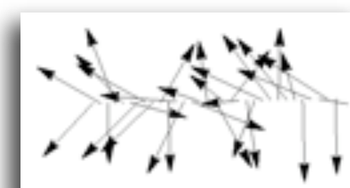




Skyrmion crystal

S. Mühlbauer *et al.* Science (2009)



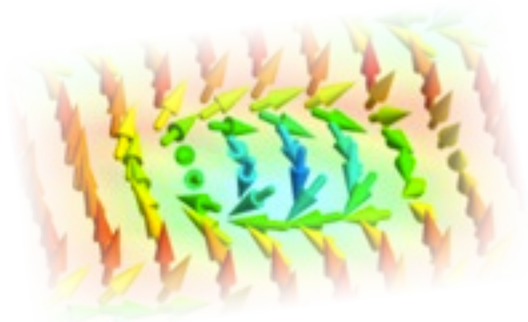


Magnetic skyrmions

Tony Skyrme (1961,1962)

stereographic projection from sphere to plane:

hedgehog



topologically stable object with quantized winding number

$$\boxed{W = \frac{1}{4\pi} \int d^2\mathbf{r}\, \hat{M} \left(\partial_x \hat{M} \times \partial_y \hat{M} \right)}$$

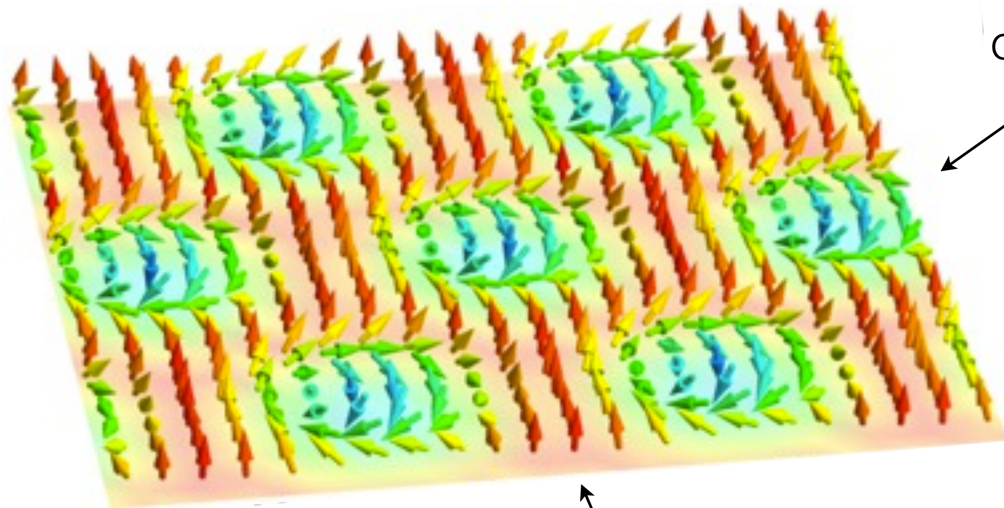
counts skyrmions!

Skyrmion crystals

Bogdanov & Yablonskii (1989)

single winding number per magnetic unit cell

magnetic
field B



chiral energy gain

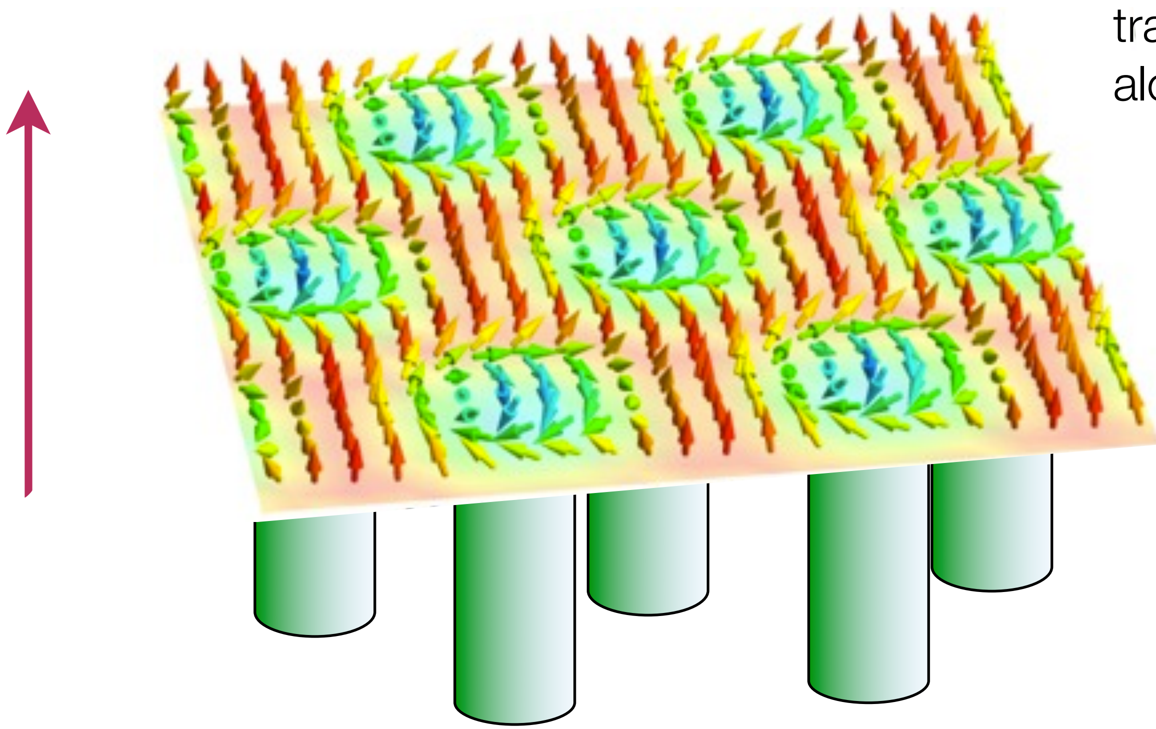
magnetic energy gain

magnetic lattice constant: ~20 nm (MnSi)
(spin-orbit coupling) ~100 nm ($Fe_{0.5}Co_{0.5}Si$)

Skyrmion crystals

single winding number per magnetic unit cell

magnetic
field B



translationally invariant
along B: skyrmion tubes

magnetic lattice constant: ~20 nm (MnSi)
(spin-orbit coupling) ~100 nm ($Fe_{0.5}Co_{0.5}Si$)

Observation of skyrmion crystals

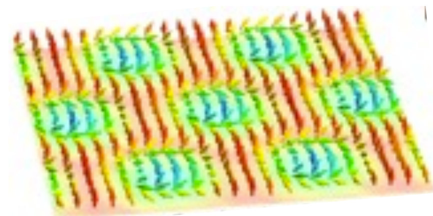
First observation:
in MnSi - neutron scattering

S. Mühlbauer *et al.* Science (2009)
T. Adams et al. PRL (2011)

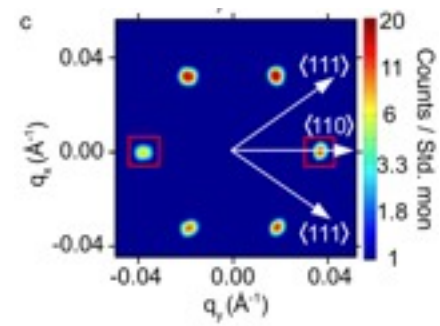
Subsequently:
in $Fe_{1-x}Co_xSi$ - neutron scattering

W. Münzer *et al.* PRB (2010)

real space



momentum space



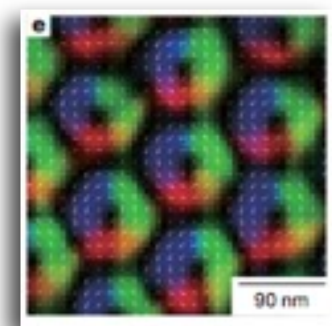
magnetic Bragg peaks: 6-fold symmetry
correlation length: ~100 μm !

transmission electron microscopy
on films: (Tokura group)

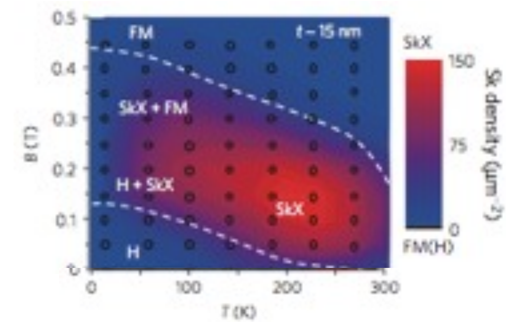
in $Fe_{0.5}Co_{0.5}Si$
X. Z. Yu *et al.* Nature (2010)

in FeGe

X. Z. Yu *et al.* Nature Materials (2011)



$Fe_{0.5}Co_{0.5}Si$



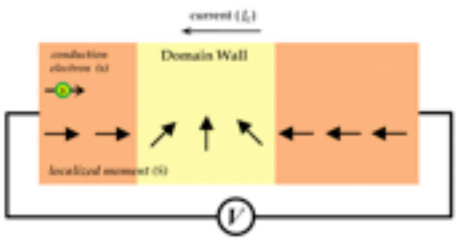
FeGe
room temperature!

Skyrmionics

coupling magnetic skyrmions to electric currents

currents couple efficiently to changes of magnetization:

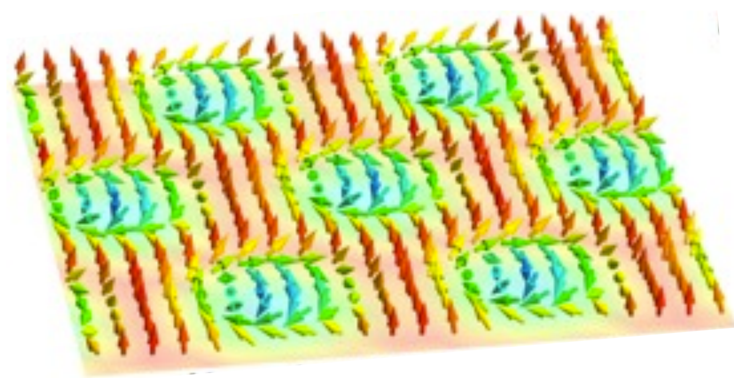
for example:



S. Maekawa (IMR, Tohoku University)

domain-wall motion in nanosized samples

Tsoi *et al.* APL (2003)
Beach *et al.* Nature Materials (2005)
Hayashi *et al.* Nature Physics (2007)



spin-transfer torque effects in a 3d macroscopic sample?

Landau-Lifshitz Gilbert equation

theoretical description: magnetic texture in the presence of spin current v_s

e.g. Zhang & Lee, PRL (2004)

$$\underbrace{(\partial_t + \vec{v}_s \nabla)\hat{M}}_{\text{Berry-phase spin torque}} = \underbrace{-\hat{M} \times \vec{H}_{\text{eff}}}_{\text{precession in effective field}} + \underbrace{\hat{M} \times (\alpha\, \partial_t + \beta\, \vec{v}_s \nabla)\hat{M} + \ldots}_{\text{damping}}$$

effective field is determined by the magnetic texture:

$$\vec{H}_{\text{eff}} = -\frac{\delta F}{\delta \vec{M}}$$

with the Ginzburg-Landau functional $F = F[\vec{M}]$

additional damping term: $(\hat{M}(\nabla_i \hat{M} \times (\alpha' \partial_t + \beta' \vec{v}_s \nabla)\hat{M}))\nabla_i \hat{M}$

Zhang&Zhang (2009), J. Zang, M. Mostovoy, J. Han, and N. Nagaosa (2011)

Skyrmionics

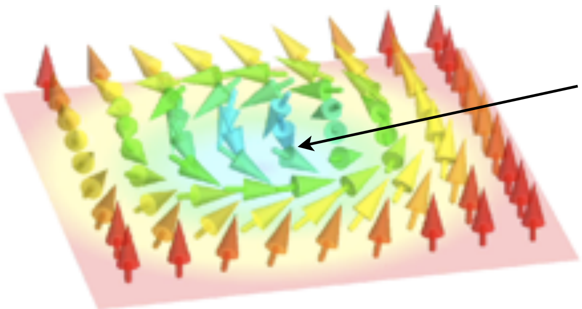
generalized Thiele approach: project LLG equation onto zero modes

A. A. Thiele, PRL (1973)

translation symmetry: center-coordinate of a single Skyrmion $\vec{x}(t)$

spin current

$\vec{v}_s$



$\vec{x}(t)$

effective equation of motion:

$$\boxed{\vec{G} \times (\vec{v}_s - \dot{\vec{x}}(t)) + \mathcal{D}(\beta\, \vec{v}_s - \alpha\, \dot{\vec{x}}(t)) = \vec{F}_{\text{pinning}}}$$

disorder:
pinning forces

magnetic texture determines

gyrocoupling vector	$G_i = \frac{1}{2}\varepsilon_{ijk} \int d\mathbf{r}\, \hat{M}(\partial_j \hat{M} \times \partial_k \hat{M})$
dissipative tensor	$\mathcal{D}_{ij} = \int d\mathbf{r}\, \partial_i \hat{M}\, \partial_j \hat{M}$

winding number,
counts Skyrmions!

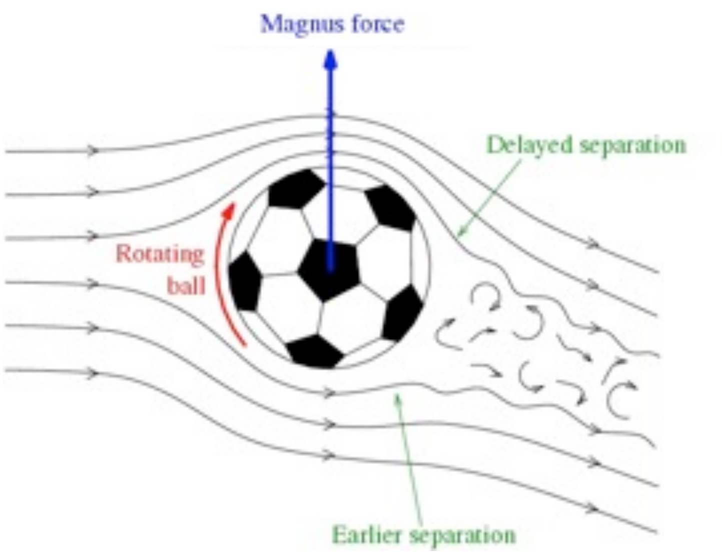
Spin Magnus force

for $\vec{F}_{\text{pinning}} \approx 0$

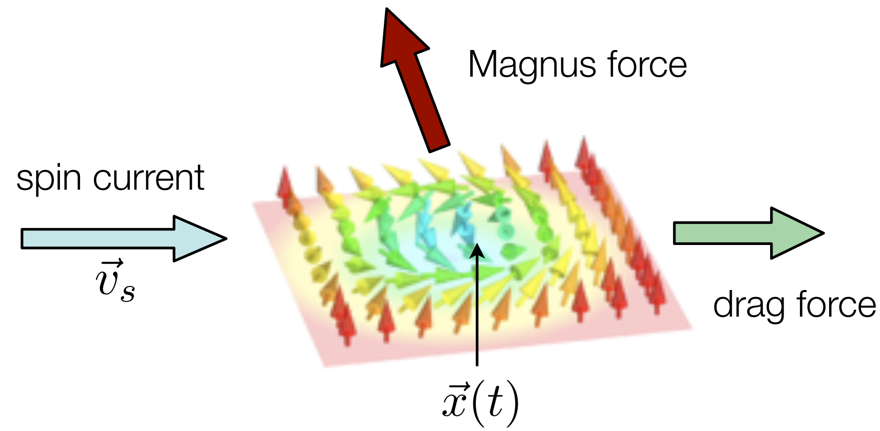
drift of the skyrmion crystal

$$\vec{G} \times (\vec{v}_s - \dot{\vec{x}}(t)) + \mathcal{D}(\beta\, \vec{v}_s - \alpha\, \dot{\vec{x}}(t)) = 0$$

in the presence of Skyrmions: $\vec{G} \neq 0$ $\Rightarrow$ transversal Magnus force



spinning ball interacting with viscous air



Skyrmion: steady twist of magnetization
≙ rotating spin-supercurrent

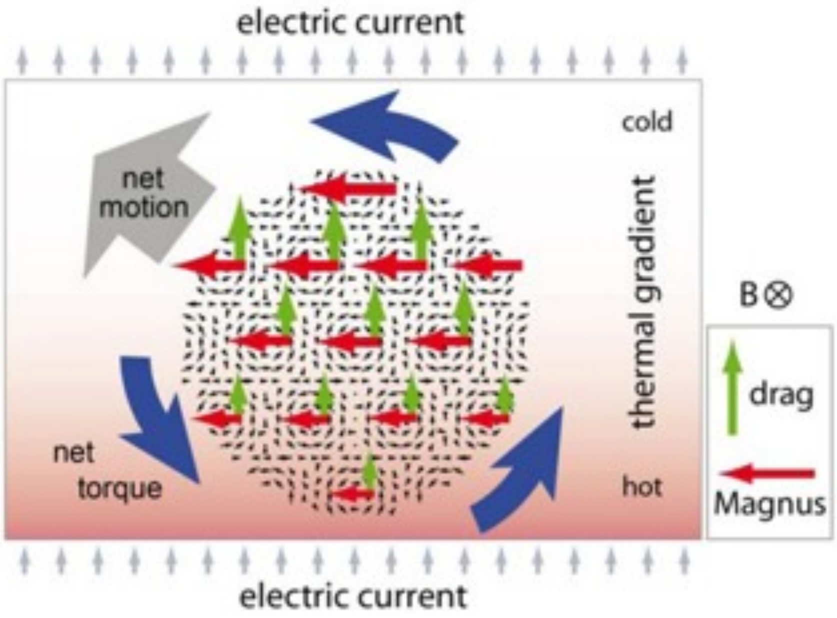
+ dissipative spin current $\mathbf{v_s}$

→ spin Magnus force

Thermal gradient-induced rotation

drift of Skyrmions not detectable with neutrons! (But with TEM! Tokura *et al.)*

use thermal gradient to generate effective forces acting on macroscopic domains



thermal gradient ⟶ gradient in **M** ⟶ gradient in spin currents

⟶ inhomogeneous Magnus/drag forces ⟶ effective global rotational torque

Thermal gradient-induced rotation

project LLG equation onto rotational mode ⇨ equation of motion for rotation angle **Φ**

$$\boxed{-\chi \sin(6\phi) = \kappa\, \partial_t \phi + \mathcal{T}}$$

tiny restoring torque due to ionic crystal lattice
6th order in spin-orbit

torque due to thermal gradient

double-transfer of angular momentum

first:	electron spin	⇔	magnetization
second:	magnetization	⇔	ionic lattice

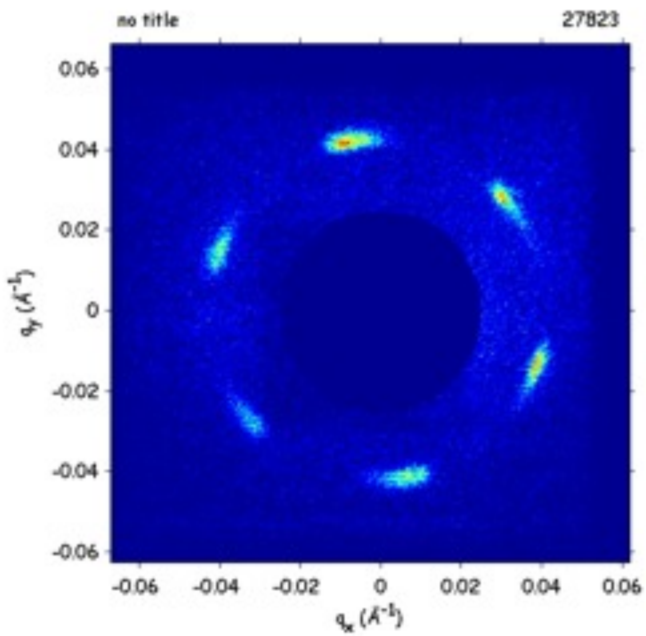
depending on domain size and applied current: finite or free rotation ($\Phi_{max} = 15°$)

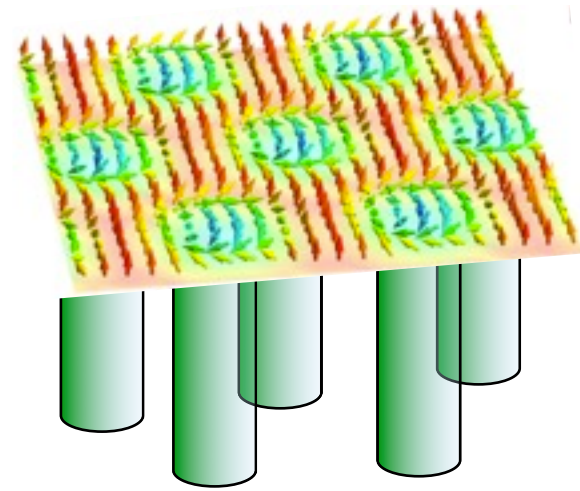
with size of domain: A

$$\kappa = \frac{A}{2\pi}\alpha\mathcal{D} \qquad \mathcal{T} = \frac{A}{4\pi}\Big[-4\pi\frac{\partial M}{\partial T}\nabla T(\vec{v}_s - \vec{v}_d) + \frac{\partial(M\mathcal{D})}{\partial T}\hat{B}(\nabla T \times (\beta\vec{v}_s - \alpha\vec{v}_d))\Big] + \mathcal{T}_{\text{pinning}}$$

Manipulating Skyrmions with current

rotation of the six-fold scattering pattern



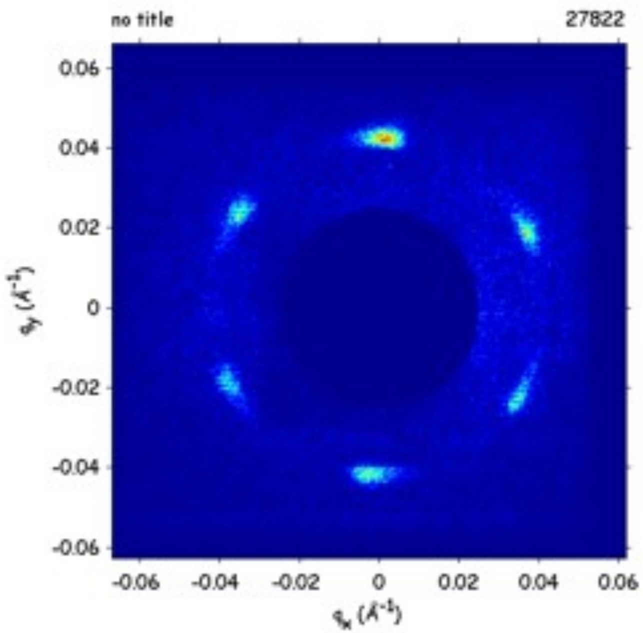


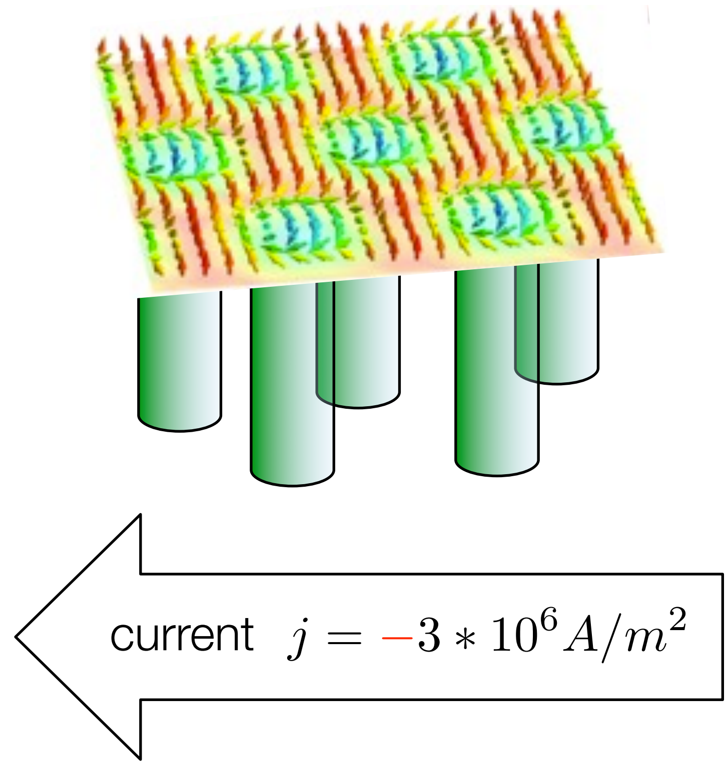
current $j = +3 * 10^6 A/m^2$

Jonietz, Mühlbauer, Pfleiderer, Neubauer, Münzer, Bauer, Adams, Georgii, Böni, Duine, Everschor, Garst, Rosch, Science (2010)

Manipulating Skyrmions with current

rotation of the six-fold scattering pattern

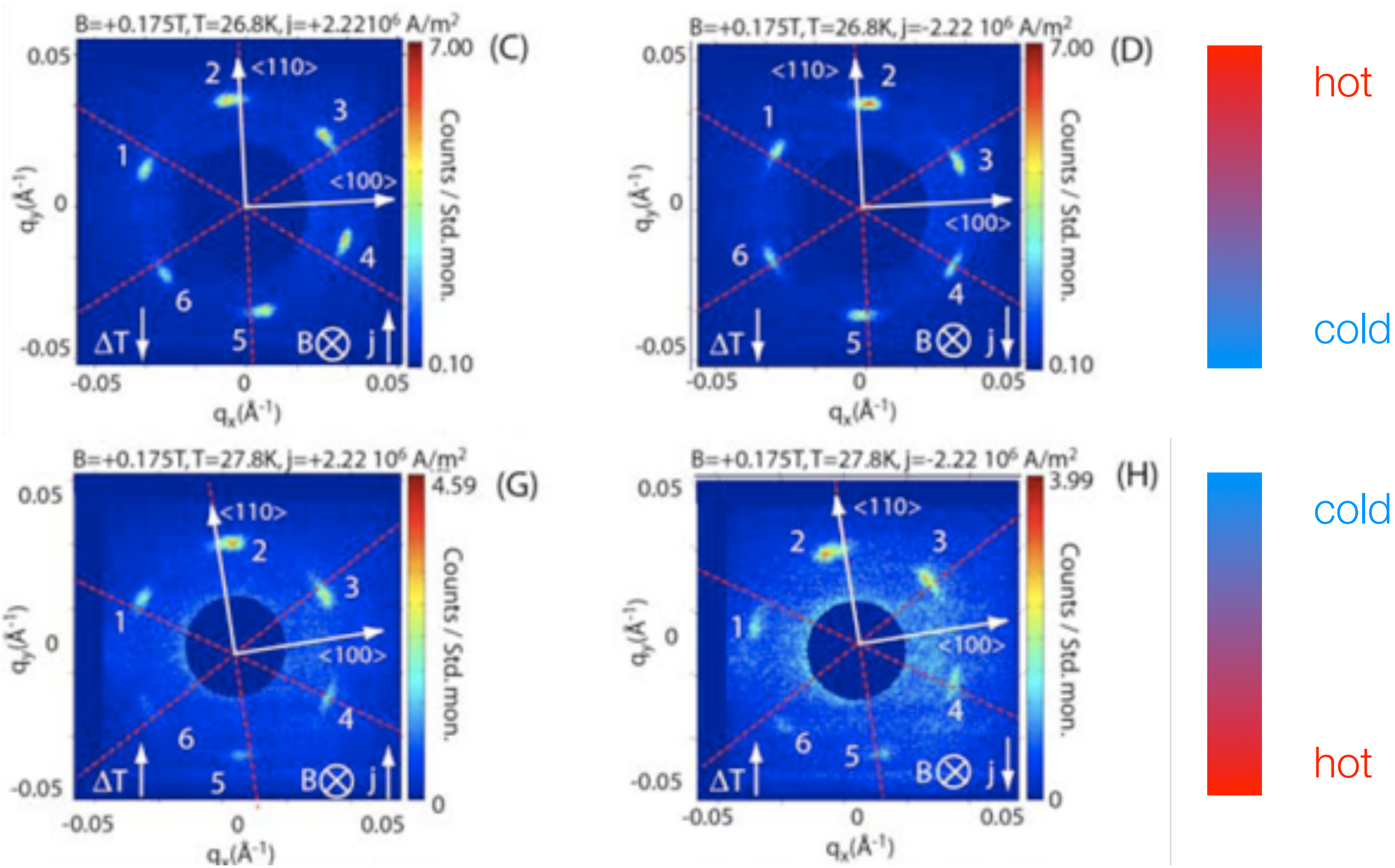




Jonietz, Mühlbauer, Pfleiderer, Neubauer, Münzer, Bauer, Adams, Georgii, Böni, Duine, Everschor, Garst, Rosch, Science (2010)

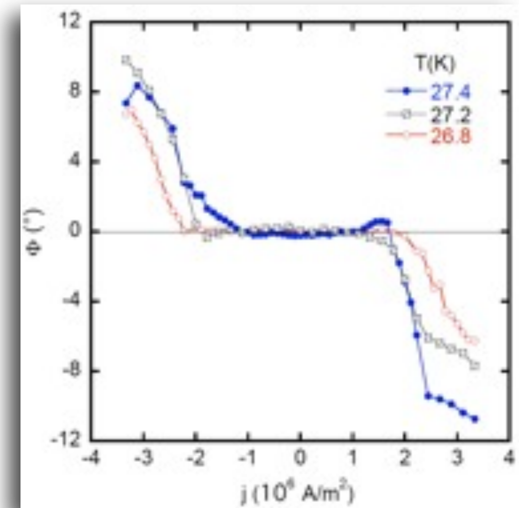
Thermal gradients

rotation proportional to thermal gradient (1K/mm) parallel to applied current



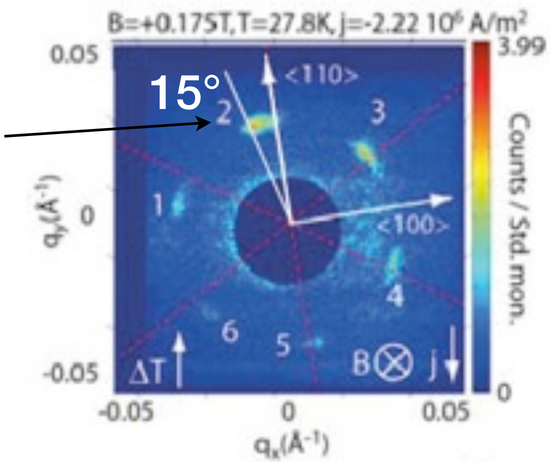
Ultra-low threshold currents

rotation angle of the scattering pattern



- no rotation as long as domain is pinned
- finite rotation beyond the depinning transition
- maximal rotation angle 15°
- free rotation for larger currents

some domains continuously rotate (comet tails)



threshold current

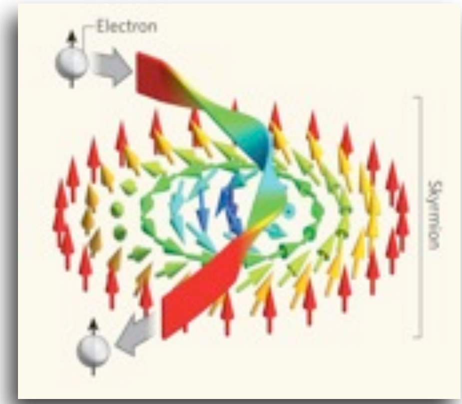
$$j_c \sim 10^6 A/m^2$$

Jonietz, Mühlbauer, Pfleiderer, Neubauer, Münzer, Bauer, Adams, Georgii, Böni, Duine, Everschor, Garst, Rosch, Science (2010)

Emergent electrodynamics in Skyrmion crystals

Adiabatic approximation

electrons adjust their spin adiabatically to the magnetic texture



Schrödinger equation for spinor

$$i\partial_t \Psi(\vec{r},t) = \Big(-\frac{\nabla^2}{2m} - \lambda \vec{\sigma}\vec{M}(\vec{r},t)\Big)\Psi(\vec{r},t)$$

Schrödinger equation for scalar

$$i\partial_t \phi(\vec{r},t) = \Big(q_e V_e + \frac{(-i\nabla - q_e \vec{A}_e)^2}{2m}\Big)\phi(\vec{r},t)$$

emergent/synthetic electrodynamic fields due to geometric Berry phase

$$\vec{E}^e_i = -\nabla_i V_e - \partial_t \vec{A}^e_i = \hat{M}(\nabla_i \hat{M} \times \partial_t \hat{M})$$

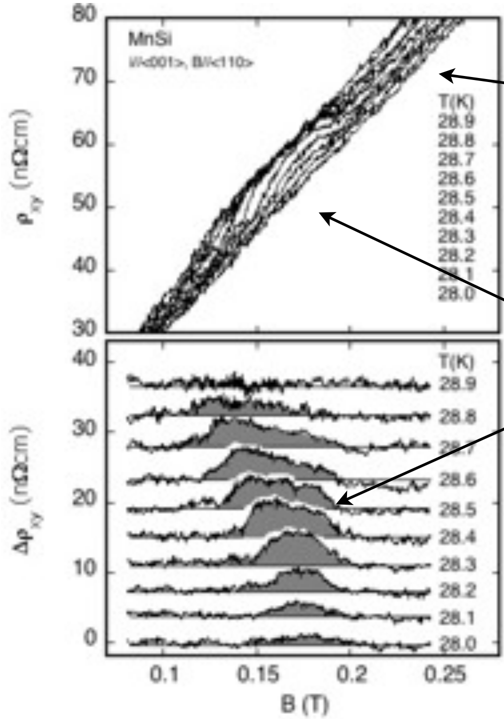
$$\vec{B}^e_i = (\nabla \times \vec{A}_e)_i = \frac{1}{2}\epsilon_{ijk}\hat{M}(\nabla_j \hat{M} \times \nabla_k \hat{M})$$

orbital magnetic field =
winding number
counts Skyrmions!

Volovik (1987), Bruno et al. (2004), Onoda et al. (2004), Zhang&Zhang (2009), ...

Topological Hall effect

emergent orbital magnetic field contributes to Hall effect



background:

anomalous Hall effect
(due to Berry-phase in k-space)

phase with Skyrmion lattice:

additional, topological Hall signal
(due to Berry-phase in real space)

A. Neubauer *et al.* PRL **102**, 186602 (2009)
see also M. Lee *et al.* PRL **102**, 186601 (2009)

⇨ topological Hall signal directly measures Skyrmion density

(one flux quantum per magnetic unit cell=2.5T orbital magnetic field)

conclusions:

- skyrmion density in chiral magnets $\longrightarrow$ spin Magnus force
- emergent electrodynamics $\longrightarrow$ topological and Skyrmion-flow Hall effect
- spin-transfer torque effects in bulk materials with small threshold current densities

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